



# NASA Armstrong Flight Research Center

## Distributed Electric Propulsion Portfolio, & Safety and Certification Considerations

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# Agenda



- NASA Aeronautics
- CAS Project Perspective
- Electric & Hybrid Electric Projects
  - LEAPTech
  - HEIST
  - Airvolt
  - X-57 Maxwell
  - FUELEAP
  - CAMIEM
  - LiON
- Future Distributed Electric Propulsion Considerations
- NASA Safety Approach
- Electric Propulsion Certification Considerations
- Wrap-up

# NASA Aeronautics

NASA Aeronautics Vision for Aviation in the 21<sup>st</sup> Century



U.S. leadership for a new era of flight

# Strategic Thrusts 3 & 4

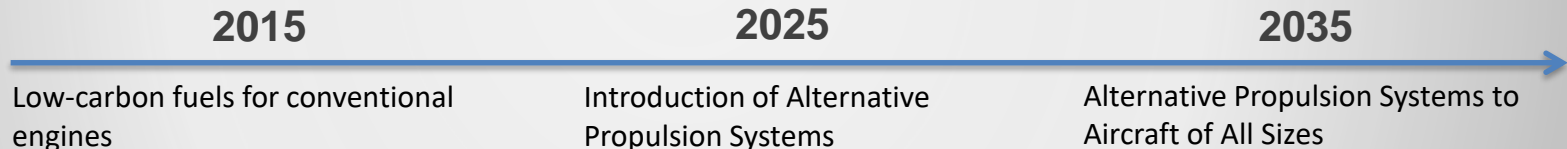
Electric Propulsion Research Themes



## Strategic Thrust 3: Ultra Efficient Commercial Vehicles



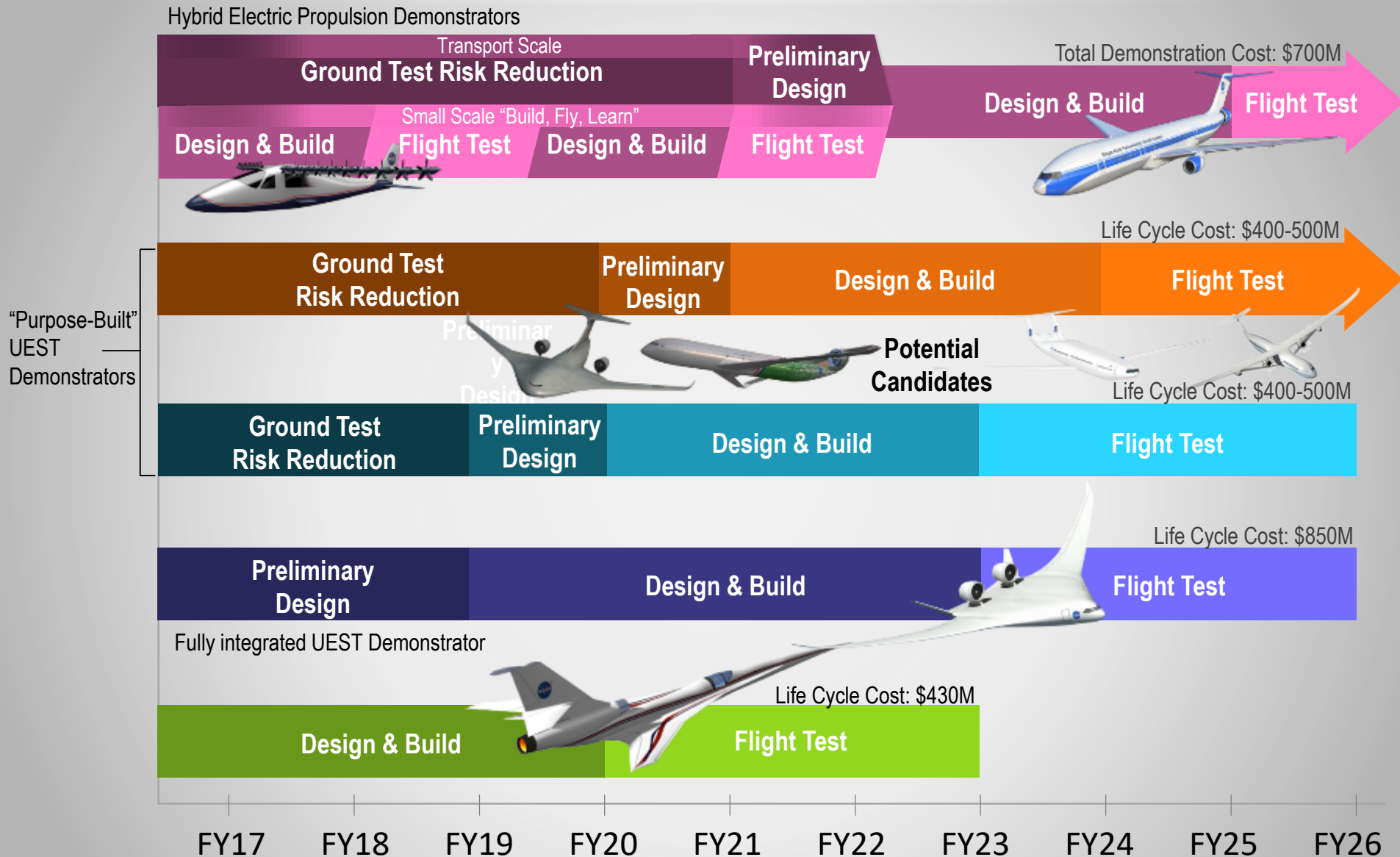
## Strategic Thrust 4: Transition to Low Carbon Propulsion



- Integrated Technology Concepts (Vehicle / Synergy)
- Power and Propulsion Architectures
- HEP Components / Enablers
- Modeling, Simulation, and Test Capability



# Electric & Hybrid-Electric Flight Demonstration Plan



# Convergent Aeronautics Solutions

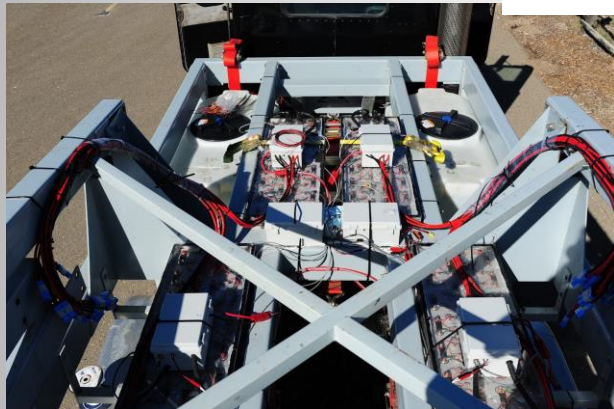
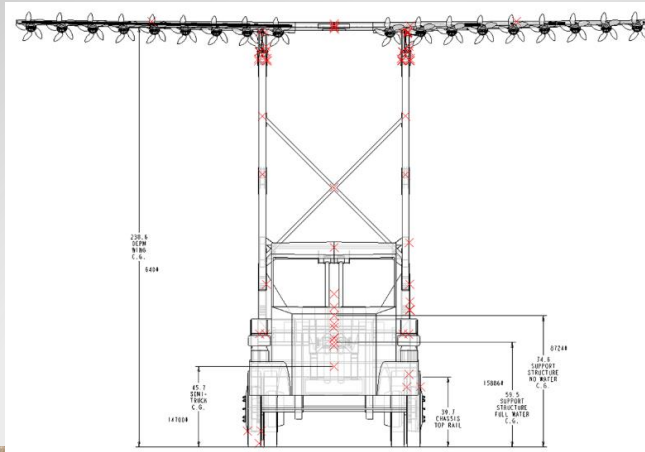
Electric Propulsion Research Themes



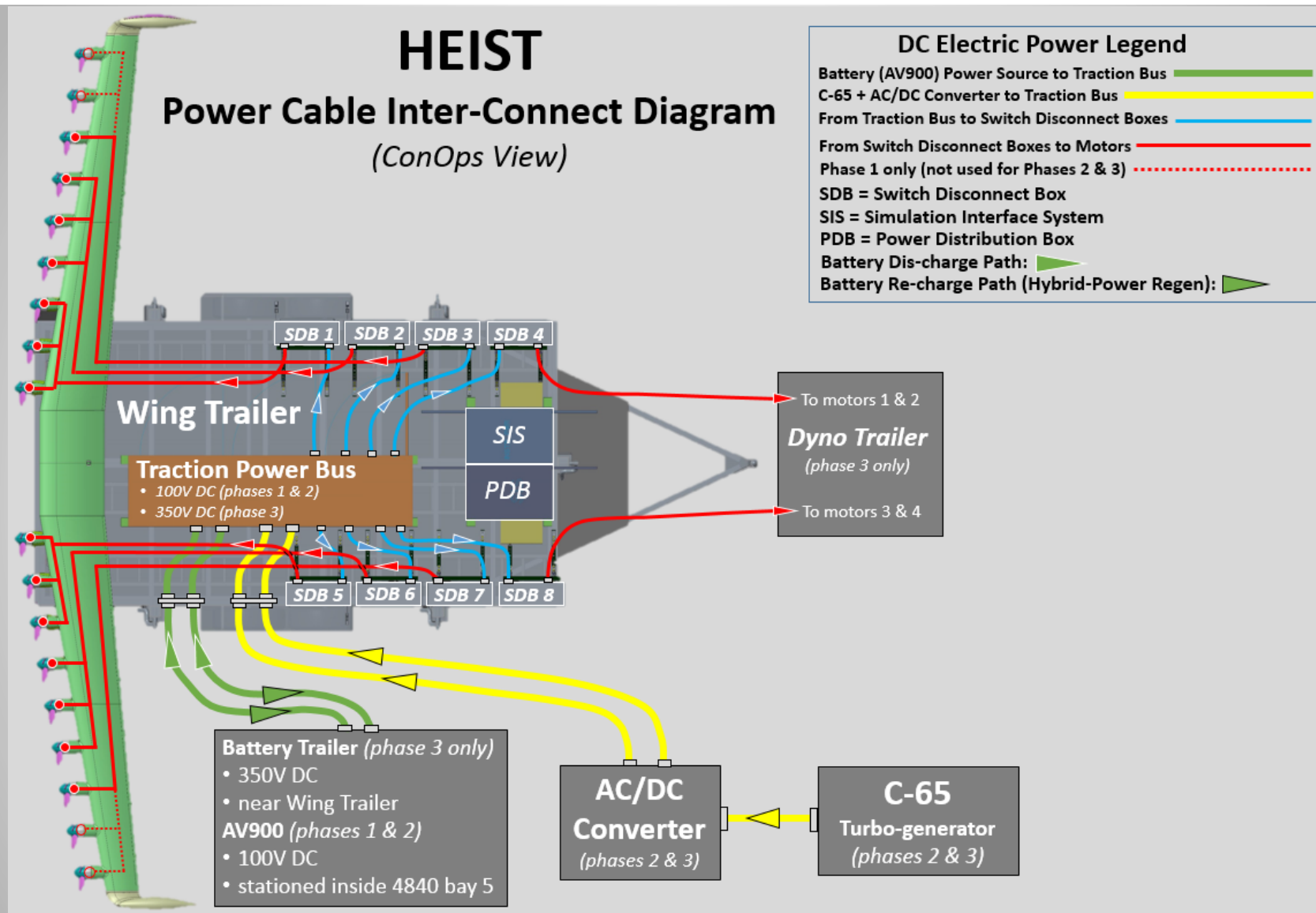
- Short project durations
- Project management – LITE
- Quickly determine technology feasibility
- Disruptive technologies
- Pulling ideas from multiple industries

# The LEAPTech Truck Experiment

1<sup>st</sup> Experiment of HEIST



# Hybrid-Electric Integrated Systems Testbed (HEIST)





# HEIST – Developing Distributed Electric Propulsion Control



Embedded  
Controllers &  
Distributed  
Intelligence

+

Power Train  
Command &  
Control Loop

+

Aircraft / Flight  
Maneuver  
Command &  
Control Loop

+

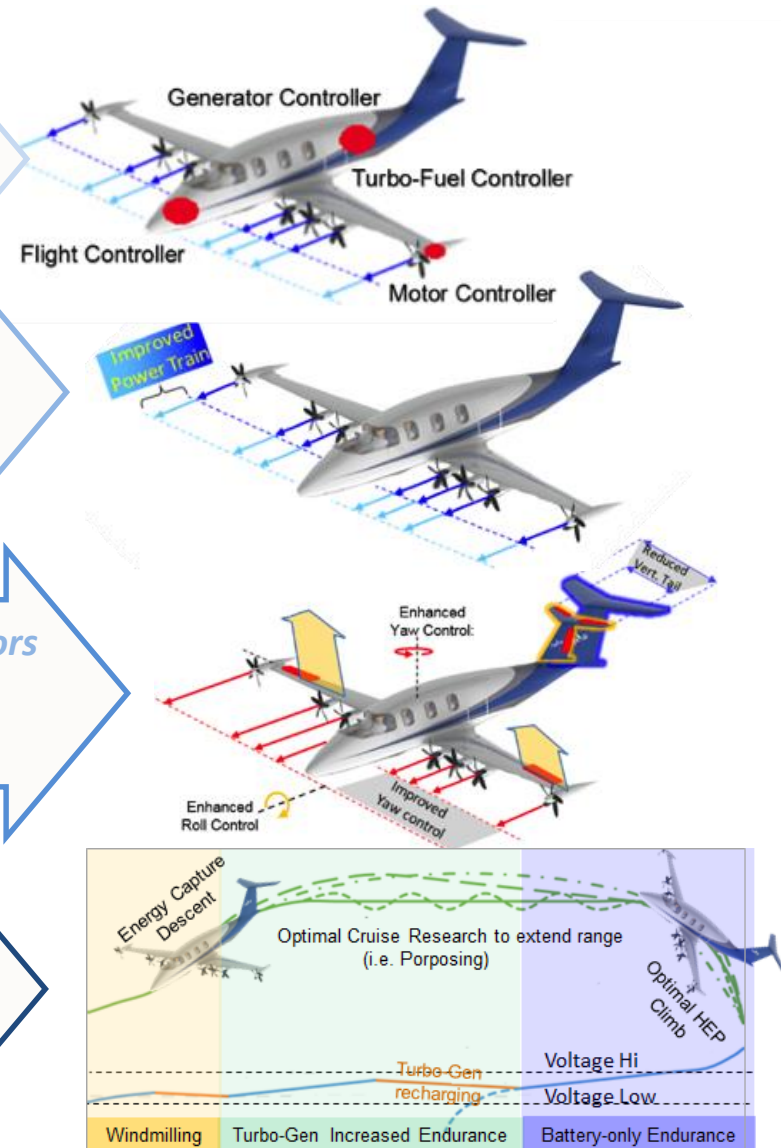
Mission /  
Operations  
Command &  
Control Loop

*Improved efficiency for each controller  
(i.e. Motor, Generator, Turbine Fuel,  
Batteries)*

*Improved Efficiency for integrated  
Power-Train*

- *Electric Motors Used as Control Effectors*
- *Reduce Vertical Tail Size*
- *Failure Recovery*

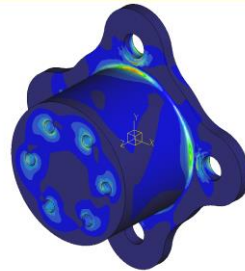
- *Peak Seeking Control*
- *Optimal Flight Profile*
- *Recharge Batteries*
- *Extend Range*



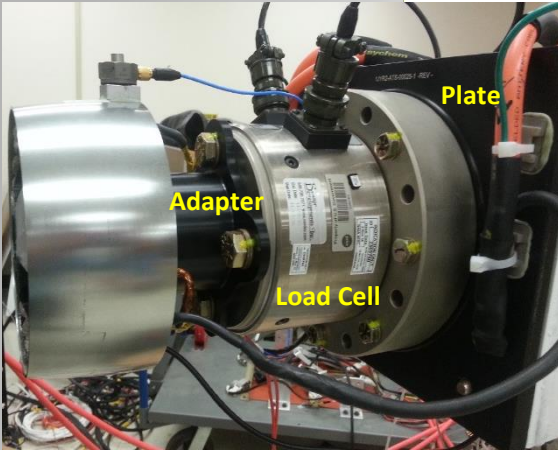
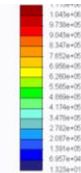
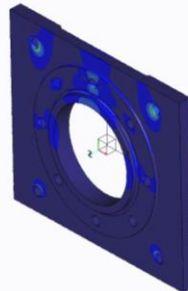
# Airvolt – Fully Instrumented, Single-Propulsor Test Stand



Sheep von Mises (WCS)  
[psi]  
LoadCell:LOADSH1 MOTOR\_ADAPTER.LW

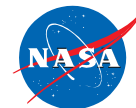


"Window" - Adapter - Adapter





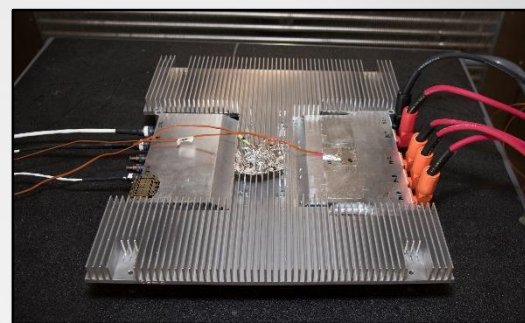
# X-57 Maxwell (SCEPTOR)



JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)



X-57 Battery Module (¼ Pack) before Short Circuit Test

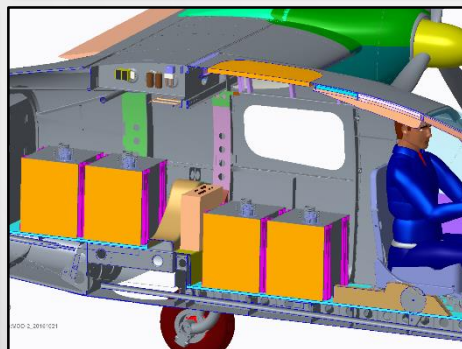


Cruise Motor Inverter Environmental Testing at NASA

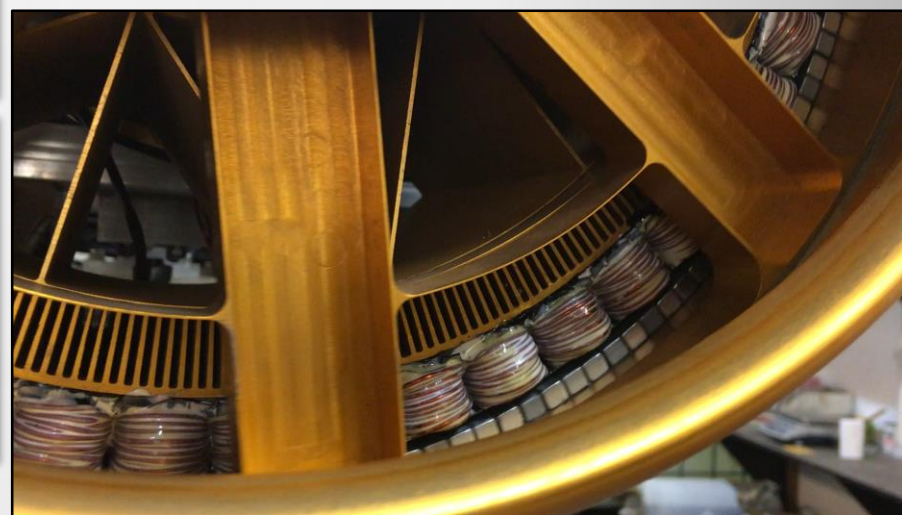
Prototype Cruise Motor



X-57 Thermal Runaway Unit (2 Trays; ½ Module)

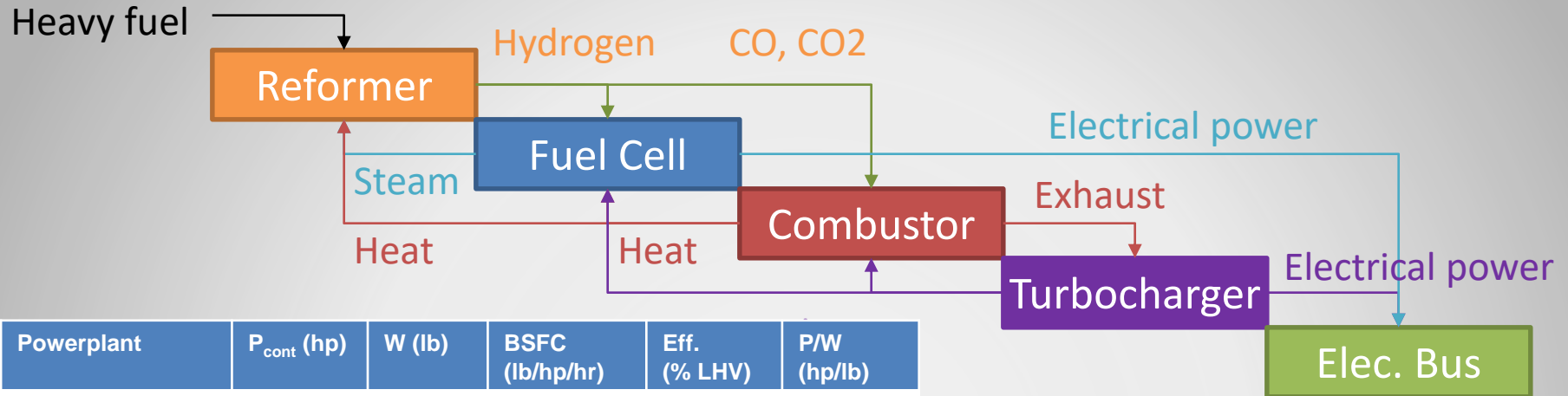


One Battery Pack (4 Module, ½ Ship Set)



# Fostering Ultra-Efficient, Low-Emitting Aviation Power

Fuel cell variant of the X-57 Maxwell



Powerplant	P <sub>cont</sub> (hp)	W (lb)	BSFC (lb/hp/hr)	Eff. (% LHV)	P/W (hp/lb)
HTS900-2	891	338	0.52	26.2%	2.63
PT6A-67D	1214	515	0.53	25.9%	2.36
CT7-9B	1750	805	0.45	30.5%	2.17
IO-550N	310	450	0.49	27.9%	0.69
R912S	100	135	0.43	31.9%	0.74
DH180A4	180	315	0.40	34.6%	0.57
AE300	168	408	0.37	37.1%	0.41
SR305-230	227	455	0.36	38.1%	0.5
Siemens 260+FC	349/258	1565	0.25	55.2%	0.22
Siemens 80+FC	107/80	470	0.25	55.2%	0.23
SCEPTOR+FC	93/66	447	0.25	55.2%	0.21
SCEPTOR	93	79/504	10.46*	92.0%**	1.2/0.18

NASA X-57 Mod II “Maxwell” Flight Demonstrator

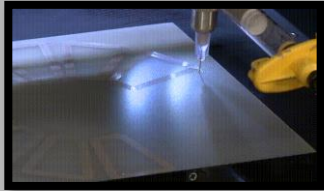


Turboshaft  
 Turboprop  
 Gasoline piston  
 Turbodiesel piston  
 Proposed fuel cell system  
 Pure battery-electric

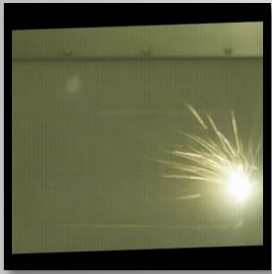


# Compact Additive Manufactured Innovative Electric Motor

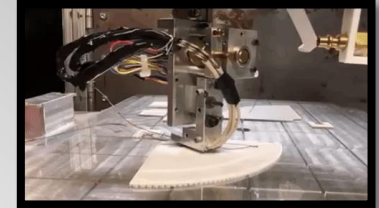
Additive Manufacturing for Electric Motors



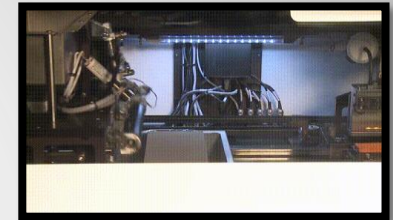
**Direct Write Printing (GRC)**



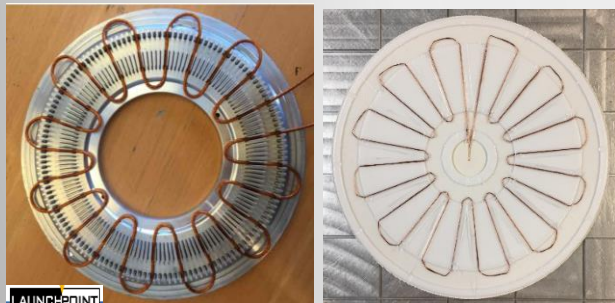
**Selective Laser Sintering (LaRC)**



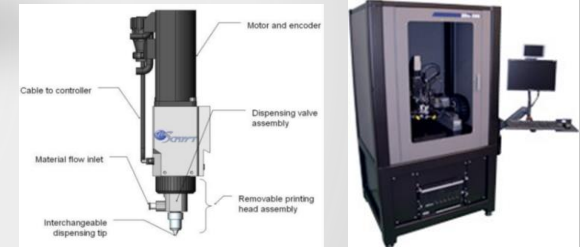
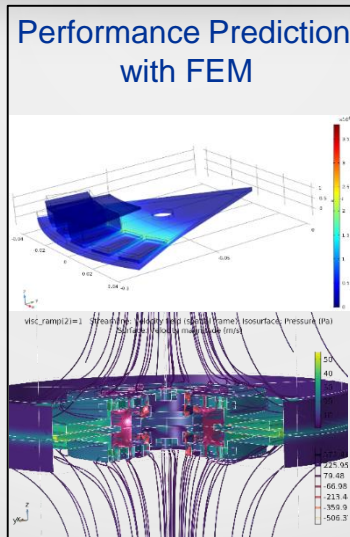
**Wire Embedding (UTEP)**



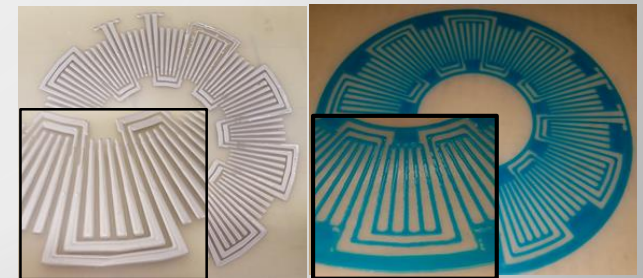
**Binder Jet 3D Printing (GRC)**



*Stator design: LaunchPoint & UTEP*



**NScript SmartPump and Direct Write Printer**



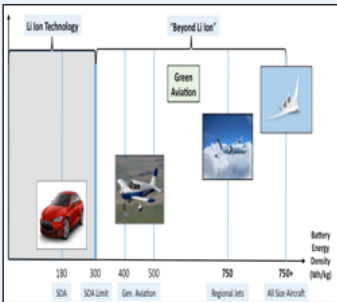
# LiON: Lithium Oxygen Batteries for NASA Electric Propulsion

Lithium – Air feasibility for flight

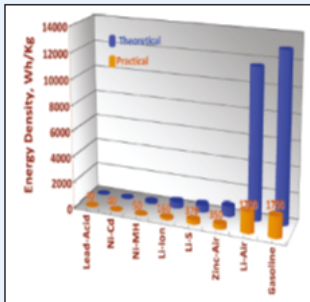


## 1. Li-Air Batteries for Electric Aircraft

**Big Question:** Can we design and build a viable battery which satisfies the significant requirements of electric aircraft

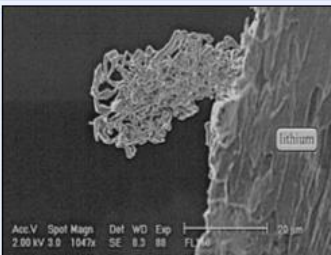


SOA Li-Ion plateaus at 300 Wh/kg. Advanced technologies required!



Li-Air has the highest theoretical battery energy density

## 2. Li-Air Battery Challenges



Electrolyte decomposition limits energy density and rechargeability



SOA electrolytes are flammable. Unacceptable for aircraft

**Electrolytes** are limiting factor for Li-Air batteries for:

- **Practical energy densities**
- **Rechargeability**
- **Safety**

**Feasibility Objective:** design/fabricate *Li-Air electrolytes* with energy densities **400+ Wh/kg** and **100+ recharges** and test in an electric UAV

## 3. Convergent Approach

Thrust Area	SOA	Transformative	
<b>Computation</b>	Empirical “trial-and-error” method	<b>Predictive computation</b> accelerates development	 Modeling
<b>New Materials</b>	Commercial “off-the-shelf” materials	<b>New materials</b> components designed and fabricated	 Aerogel Structure
<b>Decomposition Mechanisms</b>	Electrolyte decomposition poorly understood	<b>Electrolyte Design Rules</b>	 Experimentation
<b>Electric Flight</b>	Academic, laboratory studies	<b>Electric flight</b> systems modeling, instrumentation, test and analysis	 UAV Li-Air Flight

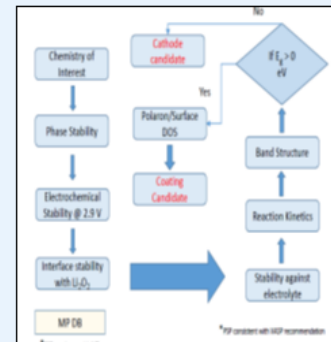
## 4. Computational Materials Screening

### Electrolyte Data Mining

PubChem ID	Predicted improvement in charging efficiency (rel. to DME)*	Available Commercially
567509	46%	✓
44719690	50%	✓
2724291	60%	✓
69609	40%	✓
99791	58%	✓

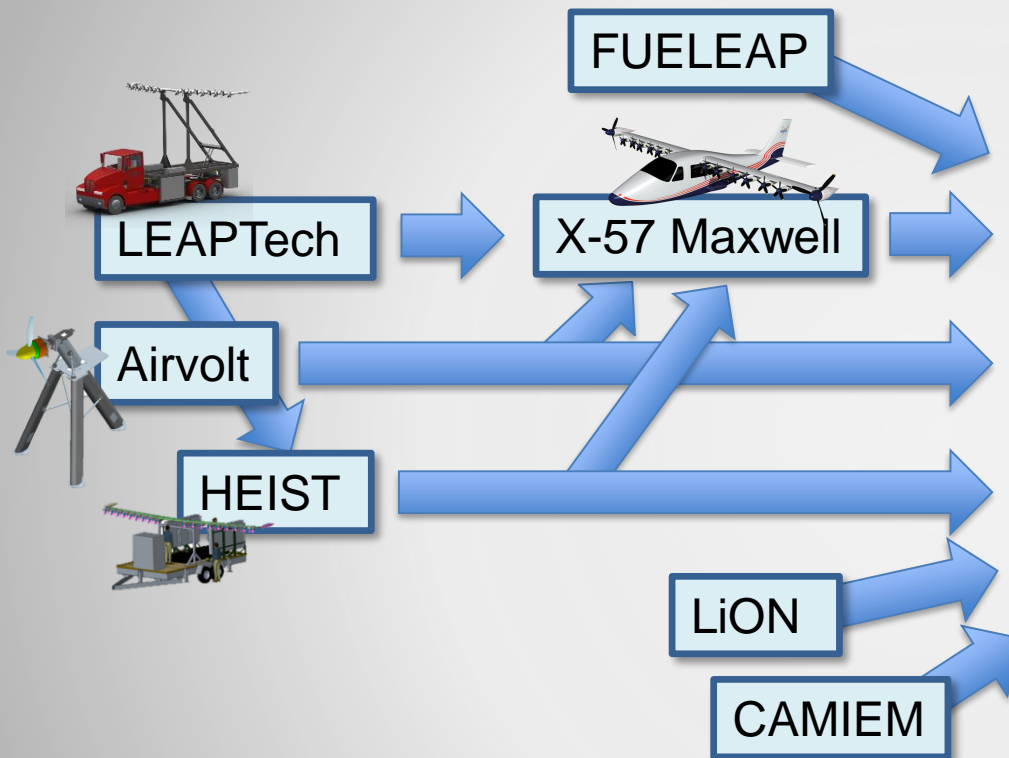
10 million database candidates screened for critical properties

### Cathode Screening Workflow

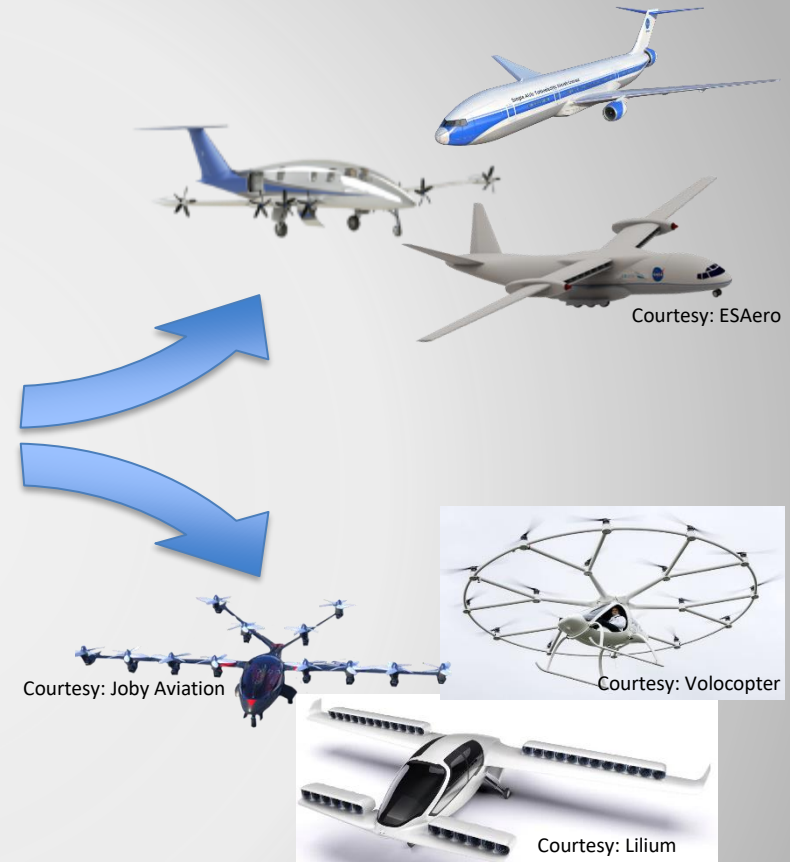


New candidates have lower operating voltages which decrease decomposition

# How the all the projects come together...



## Larger-scale DEP Architectures



## On-Demand Mobility



# Where do we go from here?



2015 → 2035

Non-cryogenic	100 kW	1 MW	3 MW	10 MW	30 MW	Superconducting
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**9 Seat**  
0.5 MW Total Propulsive Power

50-250 kW Electric Machines



**19 Seat**  
2 MW Total Propulsive Power

.1-1 MW Electric Machines



**50 Seat Turboprop**  
3 MW Total Propulsive Power

.3-6 MW Electric Machines



**50 Seat Jet**  
12 MW Total Propulsive Power

.3-6 MW Electric Machines



**150 Seat**  
22 MW Total Propulsive Power

1.5-2.6 MW Electric Machines



**150 Seat**  
22 MW Total Propulsive Power

1-11 MW Electric Machines



**300 Seat**  
60 MW Total Propulsive Power

3-30 MW Electric Machines



Left side – **motor** size,  
Right side – **generator** size  
for a twin turboelectric system  
for a **fully electrified airplane**







# NASA Safety Considerations for Electric Propulsion

# Electric & Hybrid-Electric Testbed-Specific Hazards

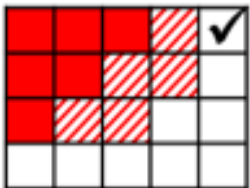



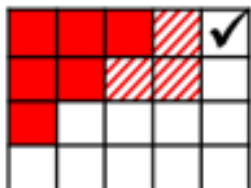





Project hazard summary	Severity/probability classification	
	Human	Asset
<b>X-57 Maxwell</b>		
HR-1 Aircraft traction battery fire	I D	I D
HR-2 Structural failure of wing	I D	I D
HR-3 Traction bus failure	I E	I E
HR-5 Aircraft damage due to exposure to excessive environmental conditions during ground operations	N/A	III D
HR-7 Wing control surface system failure	I D	I D
HR-9 Inadequate stability control	I D	I D
HR-11 Failure of motor mounts	I E	I E
HR-12 Whirl flutter	I D	I D
HR-13 Symmetric loss of cruise propeller thrust (partial/total)	II E	II E
HR-14 Avionics bus failure	III E	II E
HR-15 Cruise propeller performance degradation and/or separation	I E	I E
HR-17 Battery modules separate from attach points	I E	I E
HR-18 Abrupt asymmetric thrust	I D	I D
HR-19 Electromagnetic interference in flight	N/A	IV D
HR-20 Landing gear structural failure	II D	I D
HR-21 Failure of propulsor system	I E	I E
HR-22 Restricted and/or obstructed crew egress	I E	N/A
HR-23 Cockpit air contamination	I E	I E
HR-24 Inadvertent cruise motor propeller rotation	I E	III E
HR-25 Equipment pallet separates from attach points	I E	III E
HR-26 Personnel exposed to high voltage/current	I E	N/A
HR-27 High lift propeller damage and/or separation	Analysis in work	
HR-28 Classic flutter	I E	N/A

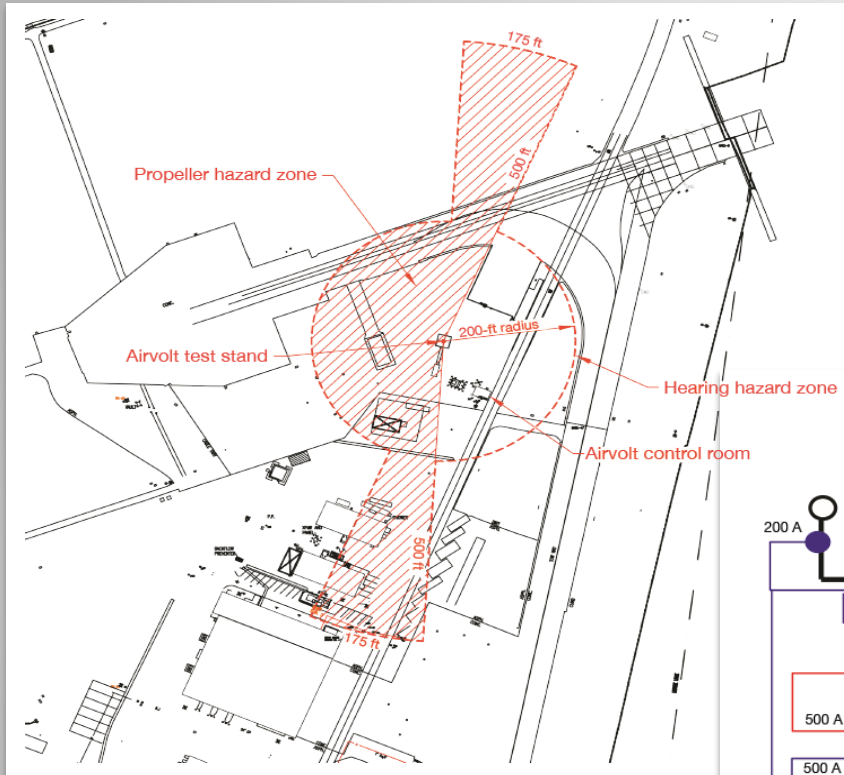
Project hazard summary	Severity/probability Classification	
	Human	Asset
<b>HEIST</b>		
HR-1 Propeller failure	I E	III C
HR-2 Traction battery fire	II E	III D
HR-3 Inadvertent system activation	I E	III E
HR-4 Electrical discharge / shock / arc flash	I E	III E
HR-5 HEIST ground asset collision	I E	II E
HR-6 JM-1 motor failure	I E	IV B
HR-7 Electrical fire	II E	III D
HR-8 Damage to HEIST assets due to environmental factors	N/A	III E
HR-9 Test article support structure failure	I E	III E
HR-10 Excessive noise exposure	II E	N/A
HR-12 Dynamometer system failure	I E	III C
HR-15 Software operation outside of intended parameters	N/A	III C
HR-16 Electromagnetic interference	N/A	IV D
HR-17 Loss of hardware communication link	N/A	IV D
<b>Airvolt</b>		
HR-1: Lithium polymer battery fire	II E	IV E
HR-2: Airvolt test stand structural failure	I E	III E
HR-3: Electrical fire	III D	II E
HR-4: Electrical discharge/shock	I E	III E
HR-5: Propeller / motor failure	I E	IV E
HR-6: Test personnel exposed to excessive noise during system operation	II E	N/A

# Example of a Distributed Electric Propulsion Hazard



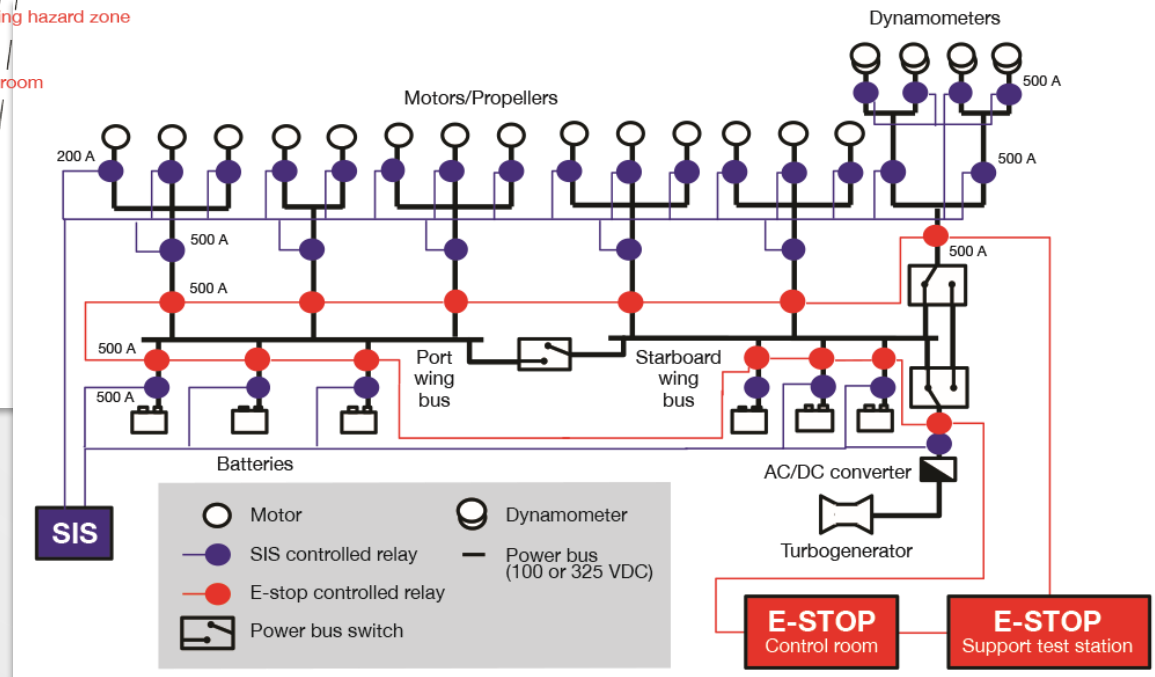
X-57 Maxwell HR-3 traction bus failure				
Causes		Effects		
A. Electrical short B. Wiring defect C. Design error D. Circuit protection component failure E. Installation error F. External/environmental abuse (thermal/mechanical) G. Grounding isolation fault H. Inadequate grounding I. Operational / procedural error J. Lightning strike		* Loss of essential avionics power * Total loss of aircraft power * Motor failure * Propeller governor failure * Fire * Damage or loss of aircraft * Damage to ground assets * Injury or death to personnel		
AFRC hazard action matrices		Mitigations		
Probability A B C D E Cat I  Cat II  Cat III  Cat IV  Human		1 Design avionics bus for single fault tolerance (A,B,C,D,E) 2 Ground test (CST) (A,B,C,D,E,F,G,I) 3 Grounding checks (G,H) 4 Design with margin (de-rate power system) (C,D,F) 5 Quality control process (B,E,I) 6 Peer review of design (C) 7 VFR operations only (J) 8 Perform visual inspection of system components (A,B,D,E,F) 9 Adhere to X-57 operational placards and procedures (E,F,H,I,J)		
Asset / Mission A B C D E Cat I  Cat II  Cat III  Cat IV  Asset / Mission				

# Distributed Electric Propulsion Hazard Mitigation Examples



Propeller and audio decibel-level threshold keep out zone

Manual hardware-only Emergency-Stop (E-Stop) relay network







# NASA Considerations for Electric Propulsion Certification

# FAR Part 33 – Aircraft Engines applicability



- Document:
  - *ANLYS-CEPT-005 Airvolt – FAR Part 33 Aircraft Engine applicability*
- Related documents:
  - FAR Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
  - FAR Part 33 – Airworthiness Standards: Aircraft Engines
  - NEMA MG 1-2014 Motors and Generators
  - CEPT-SPEC-001 Motor and Controller Specifications

FAR Part 33.7 – Engine rating and operating limitations

FAR Part 33.19 – Durability

FAR Part 33.27 – Turbine, compressor, fan, and turbosupercharger rotors

FAR Part 33.28(f) – Engine control system

FAR Part 33.43 – Vibration test (reciprocating aircraft engines)

FAR Part 33.49 – Endurance Test (reciprocating aircraft engines)

FAR Part 33.83 – Vibration Test (turbine engines)

FAR Part 33.87 – Endurance Test (turbine engines)

FAR Part 33.95 – Engine-propeller system test

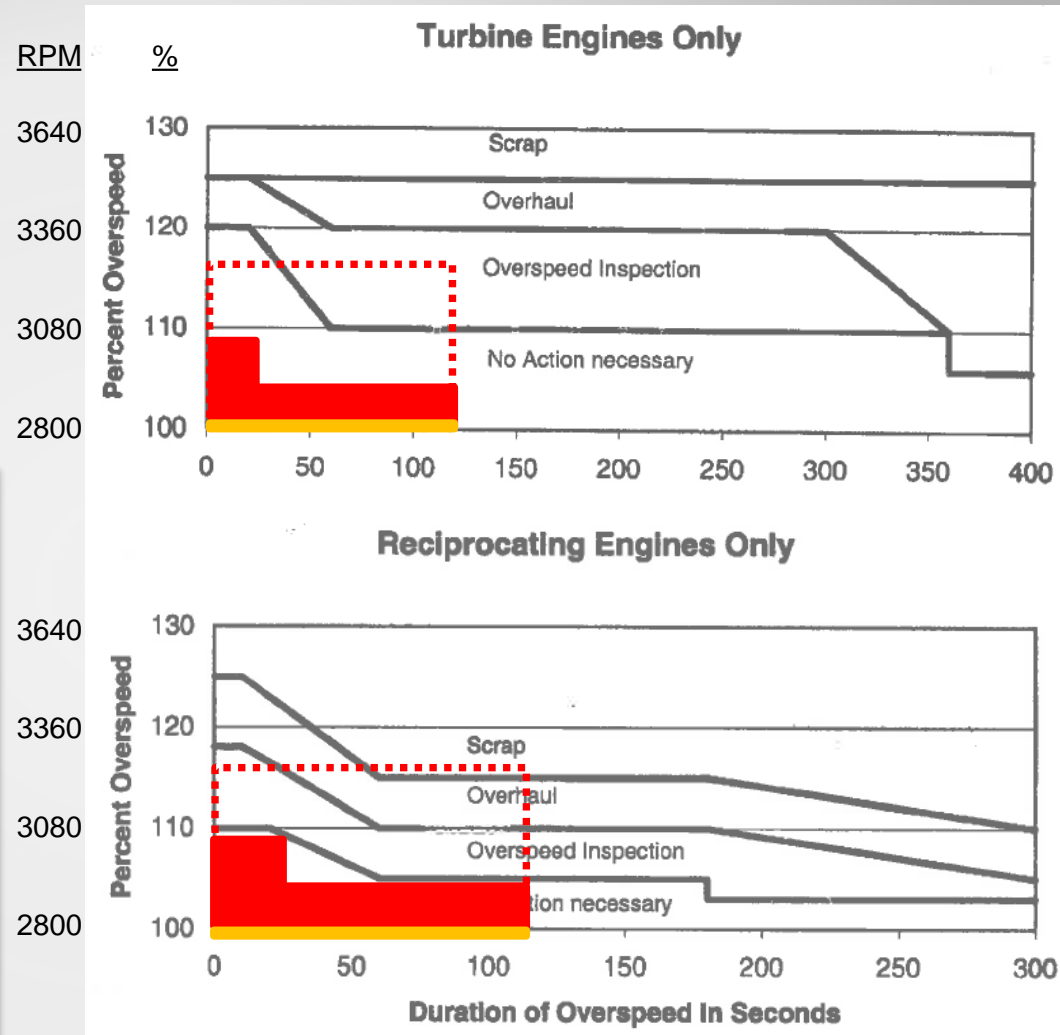
# Propeller / Motor Overspeed



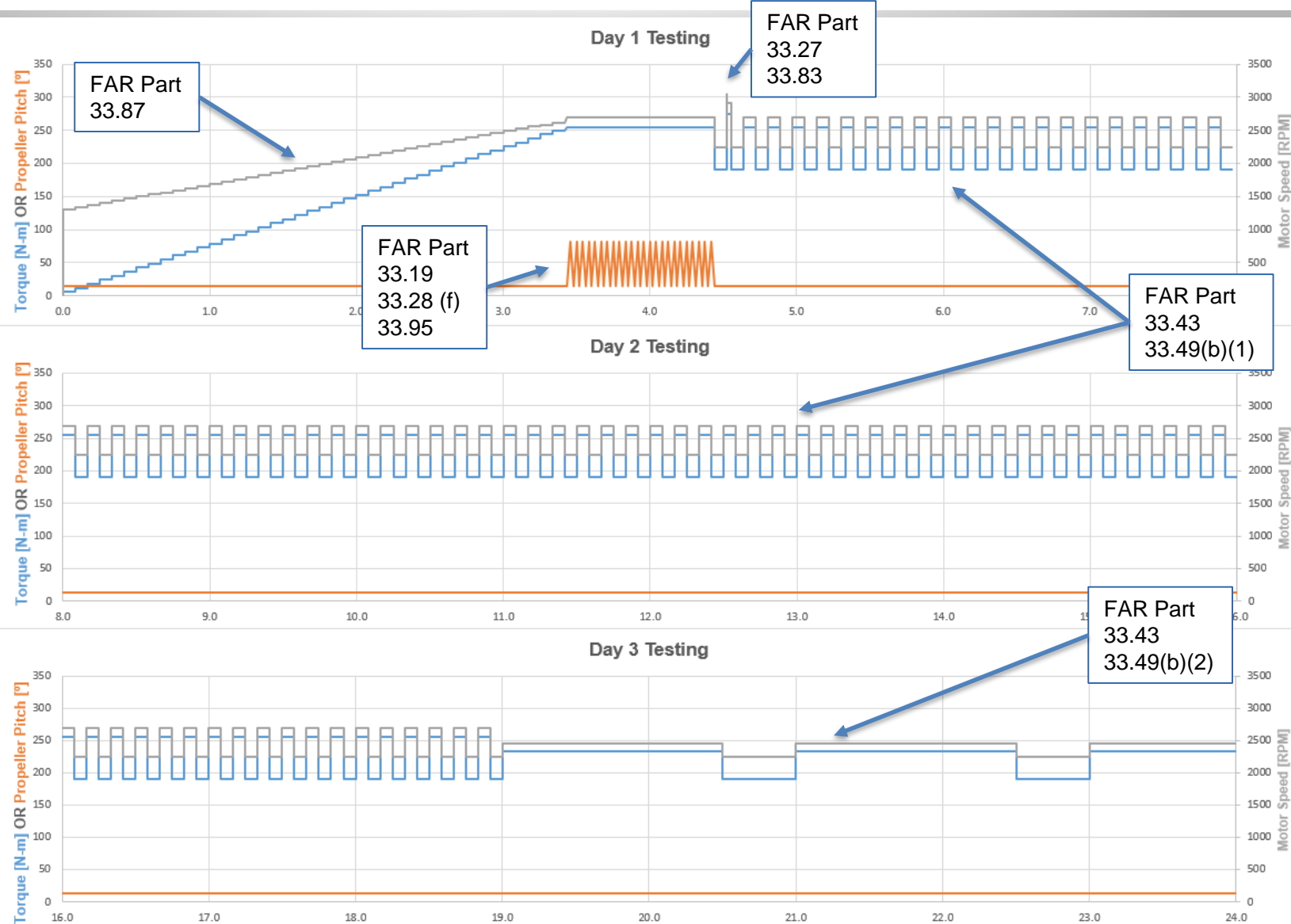
<u>RPM</u>	<u>Comment</u>
<b>3240</b>	– 120% Max Rated Speed (FAR Part 33.27)
<b>2800</b>	– 100% Rated Speed (MT-7 Propeller)
<b>2700</b>	– 100% Max Rated Speed (JMX57 Motor)

## FAR Part 33.27

- Seeks **15 min** at **120%** maximum operating speed
- **15 min** would lead to the propeller being '**Scrapped**'
- We estimated at in an emergency condition, X57 team would need **2 min** to get the plane ready for unpowered landing
- However, the propeller **may not** be able to handle at 120% for 2 min
- 25 sec – 113% (of rated motor speed)
- 95 sec – 108% (of rated motor speed)



# Motor Testing Strategy & Implementation



**Total  
Endurance:**  
79 hr \*

**Total  
Vibration:**  
>10M cycles

\*hrs 24 – 79  
of testing  
not shown



# Backup Slides

